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ScienceDirect
Energy Reports 7 (2021) 253–258
www.elsevier.com/locate/egyr

6th International Conference on Advances on Clean Energy Research, ICACER 2021 April 15–17, 2021, Barcelona, Spain

Application of light shelves in a refurbished student dormitory: Energy, lightings and comfort aspects

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Received 18 May 2021; accepted 9 June 2021

Abstract

The transparent elements of the building envelope have a crucial role not only in term of heat and mass transfers control, but also for natural light penetration, sound insulation, thermal and visual comfort of the occupants and their health. Among passive technologies, the light shelves could be architectural solutions for improving daylight penetration and for controlling thermal loads. The available research papers usually focus on one aspect. For this reason, the aim of the present study is to analyse the application of the light shelves with multidisciplinary approach and thus, taking into account: daylight, electricity for lighting, cooling and heating needs and thermo-hygrometric comfort. The case study is a real dormitory building placed in Athens and subject to a deep energy renovation toward the nearly zero energy building target. EnergyPlus, by means of DesignBuilder interface, has been used as dynamic simulation tool.

Among ten different configurations, the optimal one turns out to be the internal horizontal light shelf placed at 50 cm from the top of the window with a depth of 90 cm or 60 cm. It has been found that in some cases the reduction of electricity for lighting cannot balance the variation in heating and cooling needs.
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Peer-review under responsibility of the scientific committee of the 6th International Conference on Advances on Clean Energy Research, ICACER, 2021.

Keywords: Light shelves; Energy saving; Daylighting; Dynamic simulations; EnergyPlus

1. Introduction

The challenge for building designers is to minimize summer and winter energy need, keeping overheating within acceptable limits and also maximizing the amount of daylight entering the building, improving its uniformity. Among

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https://doi.org/10.1016/j.egyr.2021.06.043
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Peer-review under responsibility of the scientific committee of the 6th International Conference on Advances on Clean Energy Research, ICACER, 2021.

passive technology, the light shelves (LS) could be architectural solutions for improving daylight penetration and controlling thermal aspects related to the windows [1]. They usually are horizontal or inclined surfaces, placed on the inner and/or the outer side of windows, with spectral and optical characteristics such to reflect sunlight to the ceiling. The sunlight is further reflected to the room more evenly and deeply, avoiding possible glare near the opening or dark in the back zones. The performance of LSs is affected by their geometry and material, their position and inclination, the outdoor sky conditions, the indoor space layout and surface characteristics, the user behaviour. Warrier and Raphael [2] found that external horizontal LS can increase the illuminance in the inner zone by an average of 21%, but there are some configurations in which they do not improve daylight penetration or they do not reduce glare. Claros and Soler [3] showed that the LS produced the same shading effect of the overhang, bringing more light in the back part of the zone. Meresi [4] proved that the best solution for both improving the daylight distribution and protecting from glare is the combination of an external LS, with a reflection index of 90%, and a movable external semi-transparent blinds. In the study [5] also the energy consumption and the thermal comfort has been evaluated: for the West orientation if 5 shelves are used the decrease of the total energy consumption is 27.8 kWh/m^2. Kim et al. [6] found that the adoption of movable light-shelf system technology, dimming control and user-awareness is more effective for saving lighting energy and developing pleasant environments.

Definitely, the studies of scientific literature regarding the application of LS in building focus above all on the increasing of the illuminance levels [2–4,7] and in some cases on the connected reduction of the electricity for the artificial lighting [6]. Moreover, they often refer to fixed sky type for the simulations [4,8]. But this technology could influence other fields in the building, such as the cooling and heating energy need of the thermal zone and the thermo-hygrometric comfort of the occupants, since (i) they modify how the solar gains through the windows are distributed in the environment and (ii) they introduce an additional mass that exchanges thermal energy with the other elements of the environment on the basis of its thermo-physical properties and surface spectral characteristics.

The aim of this study is to evaluate the application of LS under different fields of interest: daylight, lighting energy, cooling and heating needs and thermo-hygrometric comfort. The study is conducted for a whole year by means of EnergyPlus engine, able to integrate different domains such as thermal, airflow, building services and daylight.

2. Case study

The case study is a student dormitory belongings to University of Athens and subject to a deep energy renovation toward the nZEB target. The building structure, reinforced concrete, has a rectangular profile (56.6 m × 15.4 m) with four floors above ground with a basement (Fig. 1a). It hosts 138 single-bed for students, with a total gross building area of around 3642 m^2 and a heated floor area of about 2584 m^2. The energy audit aimed at the envelope and HVAC characterization is described with all details in [9]. For the proposed case study, a numerical model (Fig. 1b) has been developed by means of the dynamic simulation tool EnergyPlus v.9 and its graphic interface Design Builder v. 6. The model has been calibrated according to M&V Guideline [10]. For instance, the error in the annual electricity consumption is about −1% and the coefficient of variation of the root mean squared error is +6%, approximately.

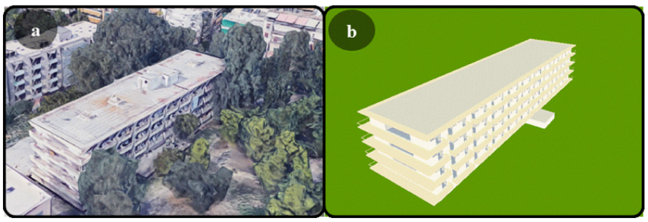

Fig. 1. The real building (a) and the building model rendering in Design Builder (b).

The building will be undergone to an energy renovation and seismic retrofitting within a European project that aims to demonstrate the attractiveness and the energy efficiency of a renovation strategy based on new façade additions [11]. In order to achieve this goal, among the various designed strategies, such as high performance materials, home automation, renewable sources integration, in this study the installation of light shelves is analysed.

3. Methodology

The study is carried out for the state of project (SP) of the refurbished building. The student rooms are characterized by a net floor area of 23 m^2 and one window of 2.7 m^2 with parapet 0.8 m high. As reference for the other ones, two representative rooms, on the West (WR) and East (ER) side, on the third floor, have been investigated. Their layout is shown in Fig. 2a. The external walls are made by cross laminated panels, with mineral wool insulation, for an overall thickness of 0.2 m and U-value of 0.33 W/m^2 K. The windows are made by triple clear and selective glass, filled by Argon, with thermal transmittance of 1.00 W/m^2 K, solar factor of 0.57 and light transmission of 0.75. All other surfaces have been designed as adiabatic, since they border with thermal zones with the same schedule of set-point temperature, occupation and use of equipment. The light reflectivity of the ceiling has been set equals to 80%; 70% for the wall, 20% for the floor as well as the reflectivity of the ground.

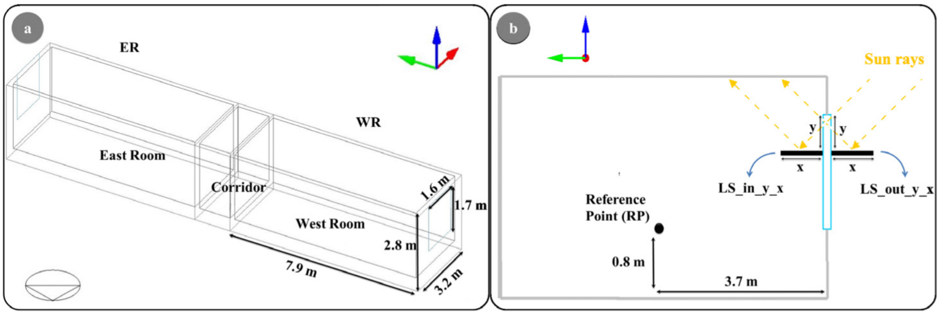

Fig. 2. Geometric features of investigated rooms (a); internal and external light shelves (b).

Following the main design criteria in literature [1], horizontal light shelves, made by wood with white coating, have been designed, both internal (LS_in) than external one (LS_out), as shown in Fig. 2b (cut view on the East–West direction). Ten geometrical configurations have been developed. They are characterized by different distance from the top of the window (y) and width (x) as shown in Table 1. For instance, LS_in_30_30 is the LS_in with a distance from the top of the window of 30 cm and an overhang of 30 cm. The geometrical, spectral and thermal features of the designed LS are reported in Table 1.

Table 1. Main characteristics of the designed light shelves.

Geometrical features		Spectral characteristics		Thermal characteristics	
Height from floor	1.9 m ; 2.1 m	Thermal emissivity	0.8	Thermal conductivity	0.03 W/m K
Distance from the top of the window (y)	50 cm; 30 cm	Solar reflectance	0.8	Density	30 kg/m^3
Width (x)	30 cm, 60 cm, 90 cm	Visible reflectance	0.9	Specific heat	1000 J/kg K
Thickness	0.03 m				

The lighting system is made by LED lamps equipped with presence and illuminance level sensors. The type of control is linear: the lights dim continuously and linearly from maximum electric power to minimum electric power, as the daylight illuminance increases. The reference point (RP) for the control is placed in the room centre at 0.8 m from the floor (Fig. 2b), assuming that the student's desk is located there.

The LSs are simulated separately for daylighting and heat balance [12]. As regard daylighting simulation, the LS_in is modelled in such way that it converts all light transmitted by windows into diffuse upgoing flux. While the LS_out, as a shading surface, blocks part of the view of the ground and so it reduces the flux transmitted through the window due to diffuse ground luminance. Regarding the zone heat balance simulation, the LS_in is equivalent to internal mass and it interacts convectively and radiatively with the zone air and other zone surfaces. For the LS_out, view factors to sky and ground are used instead, as the daylighting calculation. through this software it was possible to investigate the application of LS in the energy, thermal comfort and lighting engineering fields.

Finally, a specific hourly weather data file for Athens has been used. It defines the sky conditions through the year and it provides all elements needed during the calculations.

For the SP and all LS developed configurations, the main indices carried out are reported in Table 2. It is organized by the three fields of interest: daylighting, energy performance, thermal comfort. The results will be

Table 2. Indices carried out from simulations.

	Acronym	Description
Daylighting	Ill [lux]	Illuminance level in the RP
	El [kWh]	Electricity required for the light when the continuous dimming control is used in the RP
Energy performance	Ec [kWh]	Total cooling energy need (sensible and latent). Temperature set point (26 °C)
	Eh [kWh]	Total heating energy need (sensible and latent). Temperature set point (20 °C)
Thermal comfort	PMV [–]	Predicted mean vote according to ISO 7730 [13]. Clothing insulation: 0.5 Clo in summer; 1.0 Clo in winter
	PPD [%]	Predicted percentage of dissatisfied according to ISO 7730 [13]

shown on a time basis of the whole year and with hourly step, during four representative days: September 23 (Autumn Equinox); December 22 (Winter Solstice); March 21 (Spring Equinox); June 21 (Summer Solstice).

4. Results and discussion

4.1. Daily analysis

During the autumn equinox, in the ER the maximum illuminance magnitude (≈1700 lux for SP) is almost double than the one in the WR (≈770 lux for SP), shown in Fig. 3. With respect to the SP it is possible to obtain an increase in illuminance of up to +14%÷15% with LS_in_50_60 and LS_in_50_90 in the ER and with LS_in_50_60 in the WR. LS_out configurations bring a decrease of illuminance level, because they reduce the flux transmitted through the window due to diffuse ground luminance. Only LS_out_30_30 can bring an increasing of illuminance from +3% to +5% in the ER, during the last sunny hours of the day, and from +2% to +5% in the WR, during the early hours of the morning. The maximum energy saving of electricity for lights, by considering continuous dimming control, is reached at 14:00÷15:00 with LS_in_50_90 both for WR (−23%) and ER (−21%). Similar results have been achieved during the spring equinox.

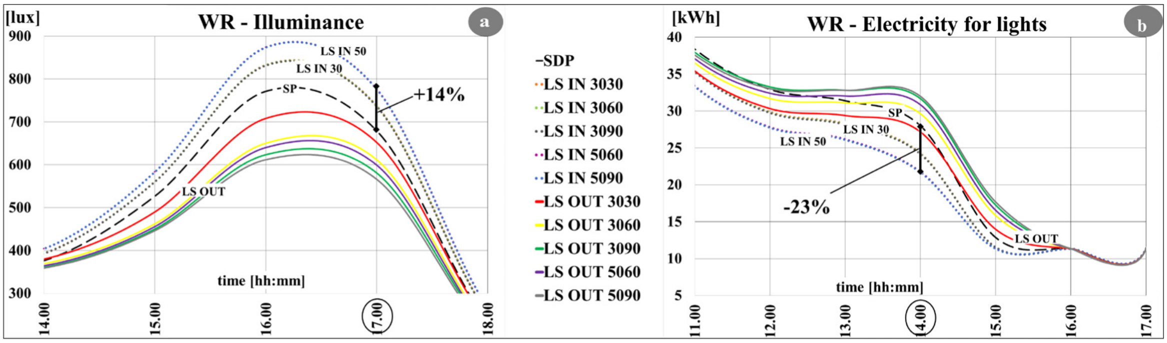

Fig. 3. Hourly values of illuminance (a) and electricity for lights (b) in the WR during September 23rd.

In the winter solstice significant reductions in electricity for lighting system have been observed, in particular of −40% at 12:00 for the LS_in_50_60 and LS_in_50_90 in the ER. For the WR the maximum reduction is −9% at 13:00–14:00 with LS_in_50_60 and LS_in_50_90 cases.

During the summer solstice the trends of illuminance are similar to the autumn solstice. Moreover, it has been observed that the cooling need in all LS_in configurations is greater than in the SP. This because there is an additional mass, near the window, that heats up and transmits thermal energy based on its thermo-physic and spectral characteristics. On the other hand, the LS_out configurations show a reduction of energy need, because they mainly act as a shading system for the windows.

For all analysed days there is no significant difference in the operative temperature values between the SP and LS cases and this condition is reflected in the PMV and PPD trends. Only during the spring day in the ER the application of LS_in_50_90 can bring an increasing of operative temperature of 1.0 °C at 12:00, while in the WR the maximum difference in operative temperature between SP and LS_in_50_90 is 0.6 °C at 18:00. For this configuration PMV values closer to the null value and reduction in PPD index have been observed.

4.2. Annual analysis

Table 3 reports the number of hours (nh), over the whole year, in which the illuminance is greater than 500 lux. It is evident that the optimal configurations under daylighting point of view are LS_in_50_60 and LS_in_50_90, both for WR and ER. With regard to the energy aspect, the percentage variations (Δ) of the thermal needs and the electricity with respect the SP are also shown. In WR the maximum reduction of electricity for the lights is −4% with LS_in_50_60 and LS_in_50_90. On the other hand, these configurations show an increasing of total cooling need of +5% and total heating need of +1%. So under the energy point of view this solution could be not suitable for the West exposure. Considering the ER, the maximum electricity reduction for the lights is observed in LS_in_50_60 and LS_50_90 cases. They also could bring a reduction of the total thermal need (heating and cooling). Finally, considering the thermal comfort aspect, the variations of the mean annual values relating to PPD with respect to the SP (Δ PPD) are shown in Table 3. There is no significant percentage variation, above all in the cases of LS_in.

Table 3. Percentage variation (Δ) of the main indices (Ec, Eh, El, PPD) with respect the state of project (SP).

	SP		LS_in_30_30		LS_in_30_60		LS_in_30_90		LS_in_50_60		LS_in_50_90		LS_out_30_30		LS_out_30_60		LS_out_30_90		LS_out_50_60		LS_out_50_90	
	ER	WR	ER	WR	ER	WR	ER	WR	ER	WR	ER	WR	ER	WR	ER	WR	ER	WR	ER	WR	ER	WR
nh	1740	724	1839	810	1838	810	1837	810	1895	863	1895	863	1727	711	1603	634	1484	574	1519	607	1484	567
ΔEc			+4%	+3%	+4%	+3%	+4%	+3%	+7%	+5%	+7%	+5%	−7%	−5%	−13%	−9%	−19%	−11%	−12%	−8%	−17%	−10%
ΔEh			−5%	–	−5%	–	−5%	+1%	−8%	+1%	−8%	+1%	+7%	+3%	+10%	+4%	+15%	+5%	+9%	+4%	+14%	+4%
ΔEl			−2%	−2%	−2%	−2%	−2%	−2%	−3%	−4%	−3%	−4%	−1%	−1%	+1%	–	+2%	+2%	+2%	+2%	+3%	+2%
ΔPPD			−2%	–	−2%	–	−2%	–	−2%	–	−2%	–	+3%	+2%	+5%	+3%	+8%	+3%	+5%	+2%	+8%	+3%

5. Conclusions

The proposed study analyses the performance of light shelves, considering not only the visual aspect, widely discussed in the literature, but also the energy performance and thermal comfort. A further aspect which is not always considered in other studies is that the analysis refers to a whole year, thus not only to some sky types. By means of a calibrated numerical model of a real case study, some general conclusions can be drawn.

Under the daylight point of view, the optimal configuration is the one that provides the internal light shelf at 50 cm from the top of the window. The depth of 90 cm or 60 cm of the panel presents comparable performance. These configurations lead to an annual increase in the level of illumination of about +12%. As regard the energy consumption for the aforementioned configurations, the savings obtained in terms of electricity for lighting not always can balance the variation in heating and cooling needs. Internal horizontal light shelf, made by wood, could be suitable for climate conditions in which the energy demand for heating is comparable or higher than that for cooling. On the other hand, the outdoor light shelves could be suitable for climate conditions in which the energy demand for cooling predominates. Under the point of view of the thermo-hygrometric comfort of the occupants, small variations in the indices have been observed ($\approx \pm$ 2% of the PPD). Finally, between the East and the West exposure, the maximum benefit of light shelves application has been observed in the room with the East exposure.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors gratefully would like to thank the financial support from the Pro-GET-one Project Horizon 2020 Innovation action under grant agreement No 723747 — Proactive synergy of inteGrated Efficient Technologies on buildings' Envelopes.

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